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(54) Optical waveguiding devices

(57) An integrated optical frequency multiplexing/demultiplexing device has a series of thin film waveguides having ribs (10, 11, 12) each partially overlaid with a tongue (13, 14) which also acts as a waveguide and feeds the next higher waveguide. Only within the region where a rib is overlaid by a tongue are the phase velocities sufficiently matched to provide coupling between waveguides at different levels. The use of semiconductive materials allows an integrated optical/electrical compound to be fabricated.

Fig.1.

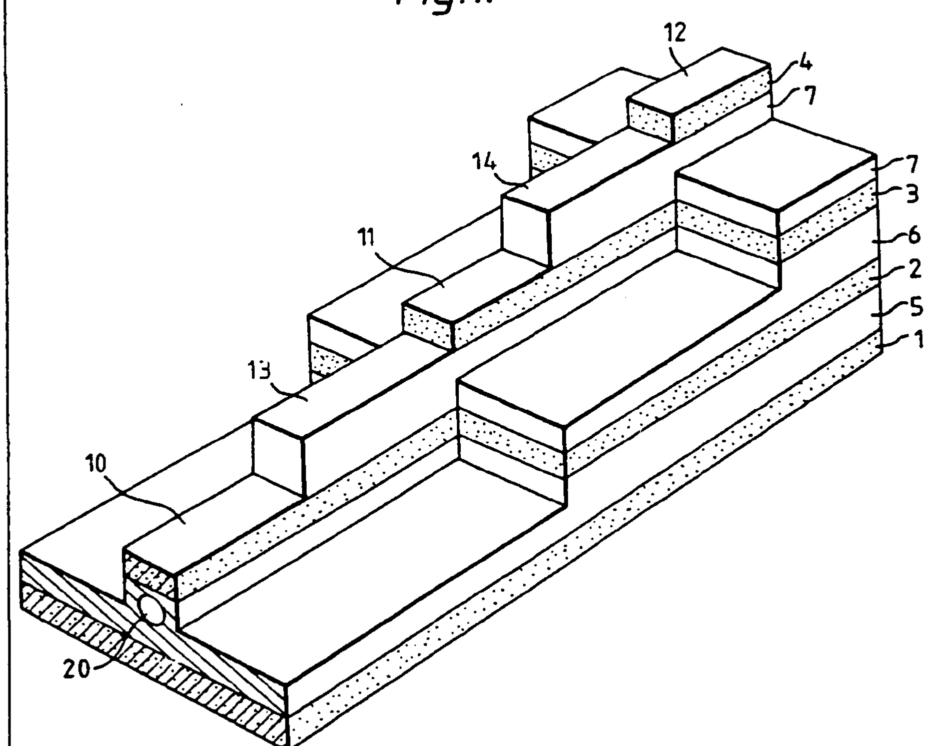

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Fig.1.

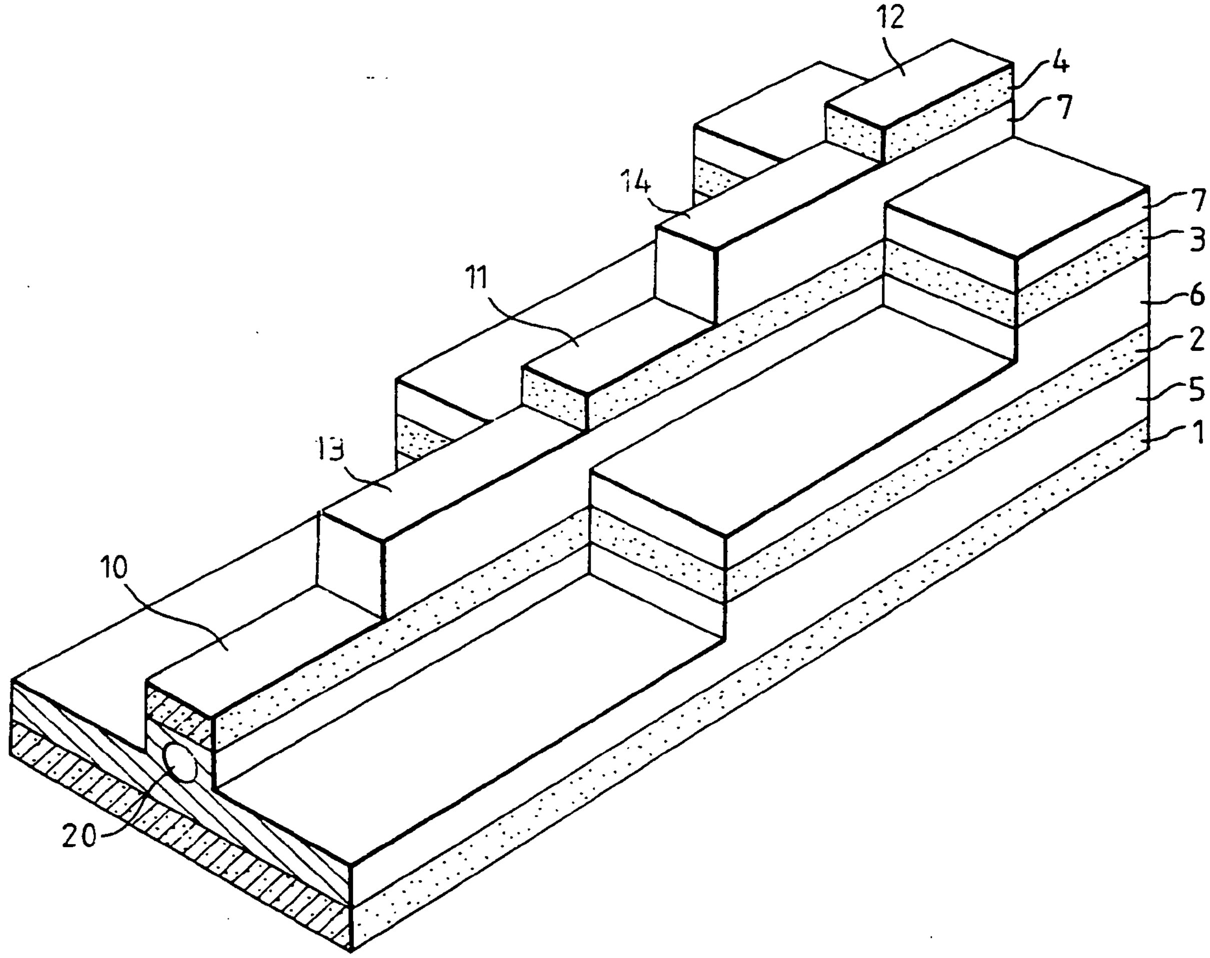
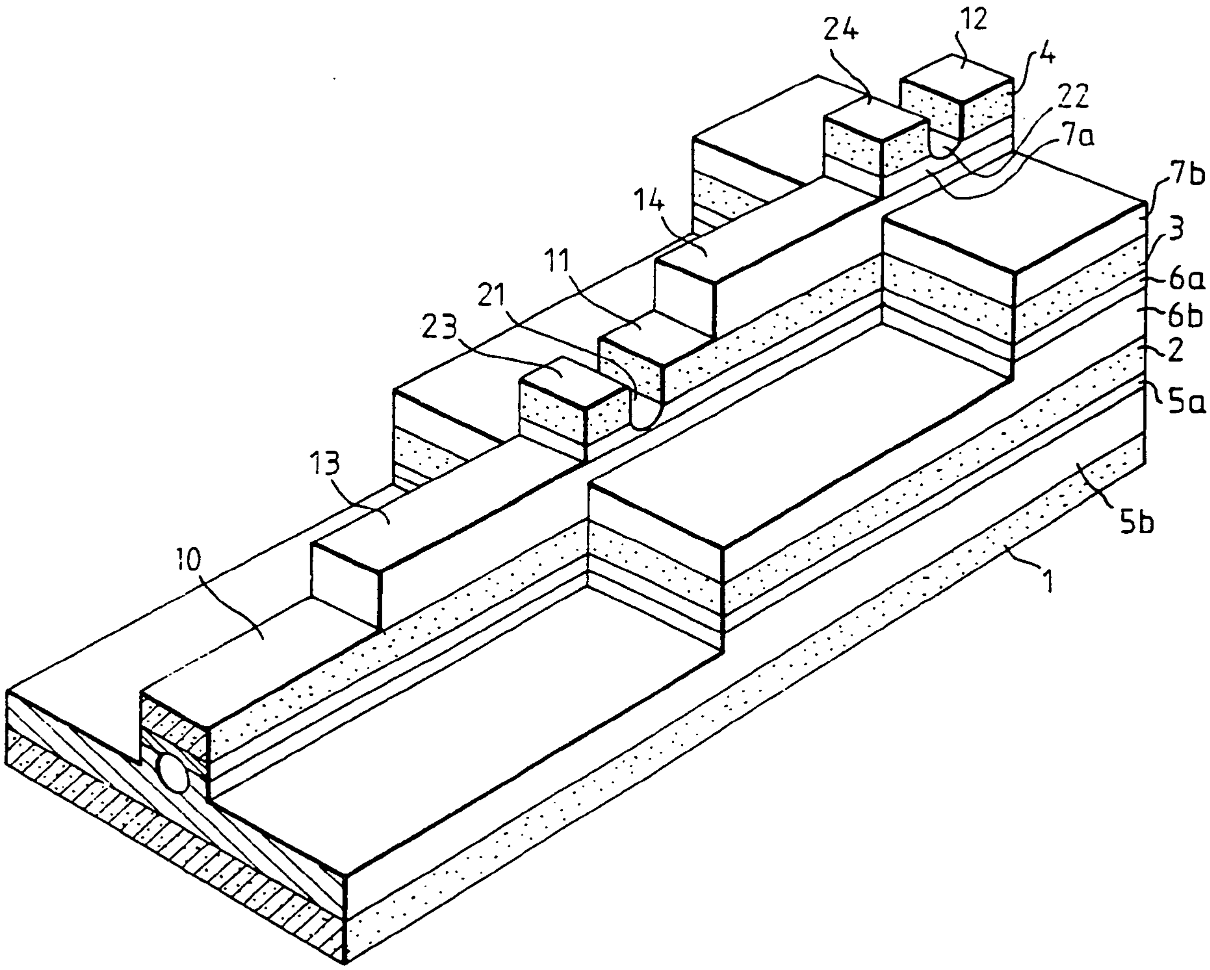


Fig.2.



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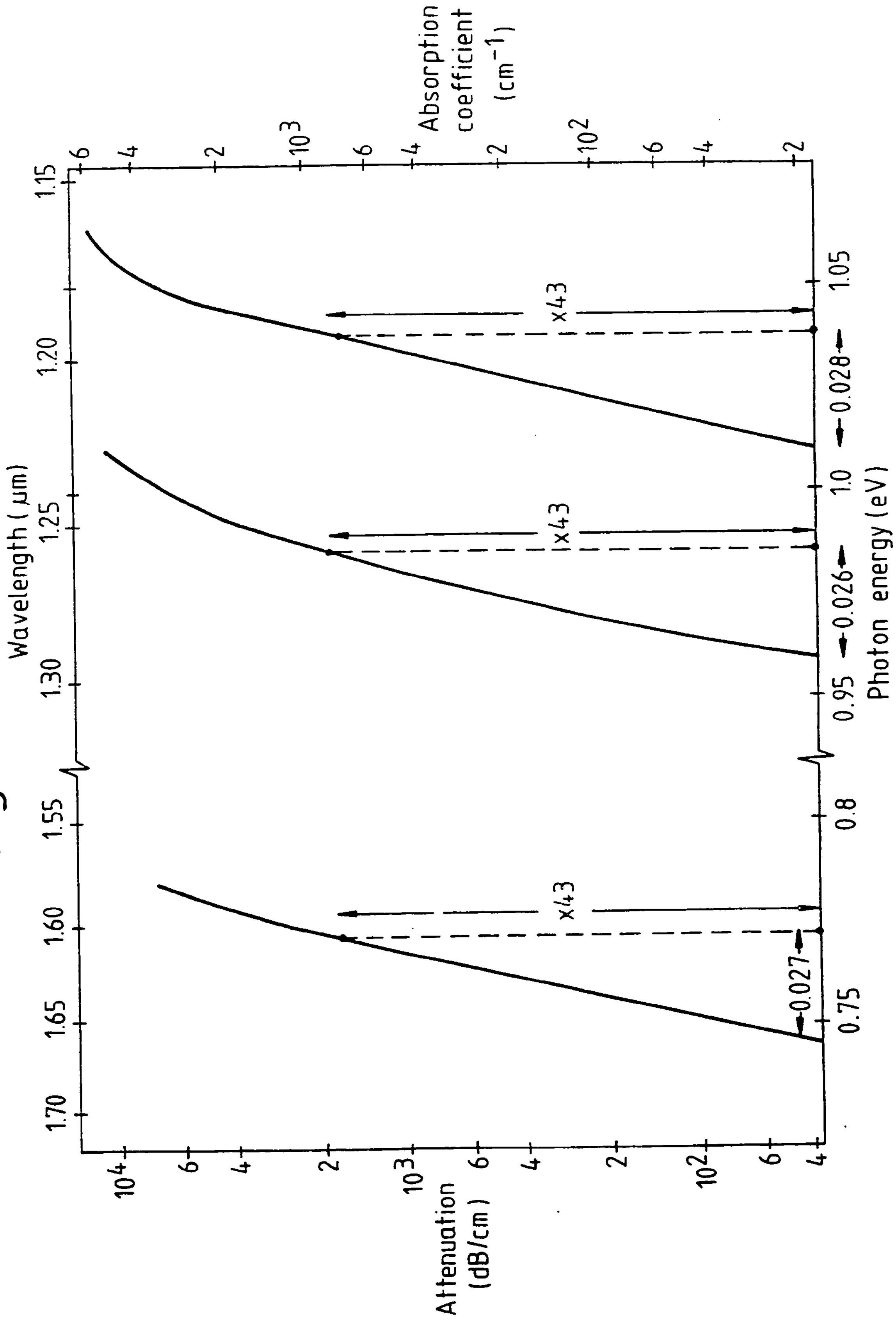
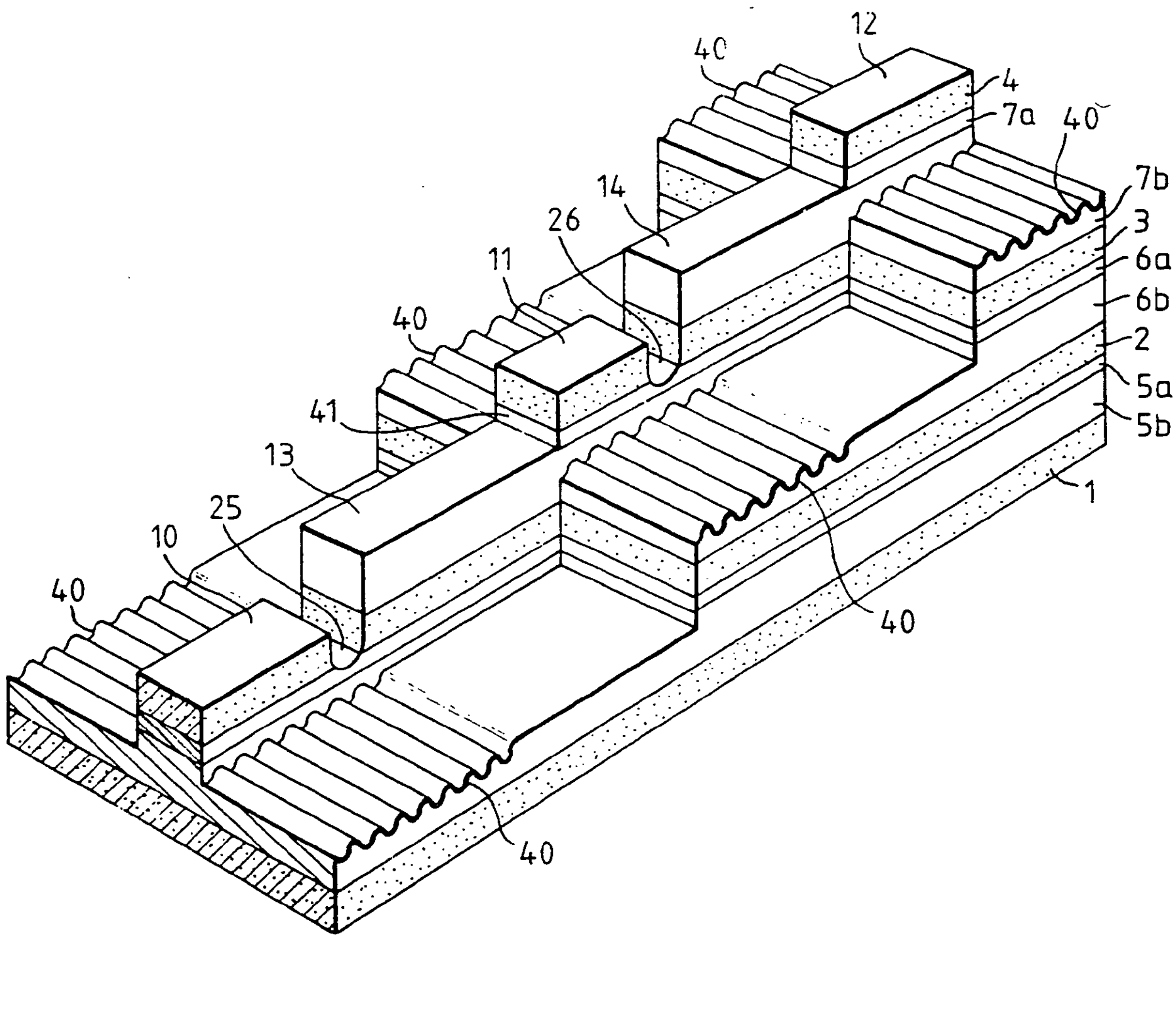

Absorption coefficient (cm^{-1})
6
4
2
10^3
6
4
2
10^2
6
4
2
Wavelength (μm)
1.15
1.20
1.25
1.30
1.55
1.60
1.65
1.70
x43
x43
x43
1.05
0.028
1.0
0.026
0.95
0.8
0.027
0.75
Photon energy (eV)
Attenuation (dB/cm)
10^4
6
4
2
10^3
6
4
2
10^2
6
4

Fig.3.

Fig. 4.



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SPECIFICATION

Optical waveguiding devices

This invention relates to optical waveguiding devices and in particular to such devices incorporating a stack of mutually coupling waveguiding structures. Such devices find application for frequency multiplexing and demultiplexing in optical fibre systems.

Frequency multiplexing provides an excellent means of upgrading the performance of optical communication systems once first generation systems have become established. It may be used either directly to increase channel capacity or, for given channel capacity, to reduce bit rate, to improve linearity, to increase repeater spacing or to economise in fibre (in wideband local networks). Perhaps of particular importance is the flexibility it confers on the way the improved characteristics may be introduced. For instance channels may be added one by one as occasion demands without interfering much with the existing system. Frequency multiplexing is therefore able and likely to provide a useful means of extending the performance in second generation communication systems.

The latest developments in optical communications are opening the way for the use of integrated optical components for signal processing. Of particular significance is the move to single mode fibre for systems operating in the wavelength range from 1.3 to 1.6 um. This move has been made to eliminate mode dispersion in the fibre so that full advantage may be taken of its low attenuation to maximise stage lengths between repeaters. The change also provides the advantage that single mode, as opposed to multimode, integrated components may be incorporated in the system at the receiver as well as the transmitter end. Single mode optical components are in general more powerful and versatile than multimode components and can in principle perform most of the many operations possible at lower frequencies in microwave waveguides. In particular they can provide the basis for practical multiplexer and demultiplexer units for frequency multiplex systems. Conveniently these units may be integrated with optical sources and detectors, in which case they must be made from appropriate semiconductor materials such as the mixed solid solutions of InP and GaAs. As such they are particularly suited to fabrication by multilayer metal-organic chemical vapour deposition or other methods which allow multilayer heterostructures to be grown with good dimensional and compositional control.

According to the present invention there is provided an optical waveguiding device including a stack of two or more superimposed optical waveguiding structures separated by low index material that permits optical coupling to occur between adjacent pairs of the waveguiding structures where their relative profiles are such that light of the same frequency will propagate in the two members of the pair with matching phase velocities, wherein the members of the stack terminate in staggered relationship, and wherein the or each of the waveguiding structures other than that at the bottom of the stack terminates in an end region over at least a part of which the profile is modified to a shape which provides a modified phase velocity which matches that of light of the same frequency propagating in the underlying region of the next beneath waveguiding structure so as to effect optical coupling therebetween.

Such devices can conveniently be made out of semiconductive material to facilitate the incorporation of electro-optic semiconductive transducer elements therein. The composition of the various layers may show a progressive grading so that the any particular part of any one of the waveguiding structures is constructed of a material having a higher band gap and lower refractive index than that of the equivalent part of the waveguiding structure next above it. The device may then incorporate a set of photodetectors each of which detects light up to a particular long wavelength limit (set by the material from which it is constructed) and is arranged to allow the passage of light of longer wavelengths for coupling to the next higher photodetector, which, because it has a smaller band gap, detects light up to a longer longwavelength limit than the preceding detector of the lower level. In this way the individual channels of a multiplexed signal can be separately detected in sequence. By replacing the detectors with light sources and operating the device in the opposite direction a set of signals can be impressed on optical carriers of different frequencies to produce a multiplexed optical signal output.

There follows a description of optical waveguiding devices embodying the invention in preferred forms. The description refers to the accompanying drawings, in which:—

Figure 1 depicts a perspective view of a first optical waveguiding device according to the invention.

Figure 2 depicts a modified form of the device of Fig. 1 adapted to function as a channel dropping demultiplexing detector.

Figure 3 is a graph showing the absorption as a function of wavelength for different semiconductive materials, and

Figure 4 depicts a modified form of the device of Fig. 1 adapted to function as a channel inserting multiplexing source.

The device of Fig. 1 is a seven layered dielectric or semiconductor structure formed from alternate low refractive layers 1, 2, 3 and 4 separated by higher refractive index layers 5, 6 and 7. The lowest layer, layer 1

extends uninterrupted the full length of the device, but the two layers immediately above it have two portions removed so as to define, over a portion of their length, a rib 10, typically 4 to 5 microns wide. The next two layers, layers 6 and 3, have corresponding portions removed to define a second rib 11, the upper part of which terminates above the root of the first rib 10. From the end of the second rib protrudes a tongue 13, typically 40 to 50 microns long, of the material of layer 6 overlying part of the length of the first rib 10. Finally, layers 7 and 4 have similar portions removed to define a third rib 12 and protruding tongue 14.

In the region up to the point where it is covered by the tongue 13, the first rib 10 functions as a rib waveguide in which, by virtue of its shape and the presence of the interface between the lower refractive index upper part of the rib and the higher refractive index lower part, the optical field will be concentrated to a cross-section indicated generally by the circle 20.

Layer 2 is thin, and so the evanescent field associated with light guided by the rib 10 will penetrate through the upper part of the rib and into the higher refractive index region of the tongue 13 formed from layer 6. This tongue also acts as a waveguide, and its cross-section is chosen so that for light of any given operating frequency, the phase velocity in this guide matches that of light of the same frequency propagating in the waveguide immediately beneath this tongue. As a result of this matching, the two waveguides are coupled, and hence propagating light energy is transferred between them. The length of the tongue 13 is chosen so that power transfer into layer 6 is substantially at a maximum at the root of the tongue 13, where it is overlaid by the material of layer 3 to form the rib 11. If the geometry were to remain unchanged at this point, the coupling between layers 5 and 6 would result in the energy being coupled from layer 6 back into layer 5. This is prevented by arranging for the geometry to change in such a way as to eliminate the coupling between these two layers by destroying the match between the phase velocities of light propagating in those two layers. Since the coupling length determined by the length of the tongue 13 is typically many tens of wavelengths long, a mismatch in phase velocity of a few percent is adequate to destroy the coupling. This is achived primarily by the small change of effective refractive index of the waveguide introduced by the presence of the material of layer 3 in the rib 11.

In this way light originally guided by rib 10 is transferred to be guided by rib 11, later to be transferred again to be guided by rib 12, and so on up the cascaded structure. For light propagating in the reverse direction the coupling is in the opposite direction, and light guided by rib 12 is transferred via rib 11.

The device of Fig. 1 (and also that of Fig. 3 and that of Fig. 4) is essentially a cascaded structure, and hence by the addition of further layers the numbers of elements in the cascade can be increased to suit applications requiring increased complexity.

Fig. 2 shows the basic device of Fig. 1 adapted to form a channel dropping demultiplexer detector. This device is formed in semiconductive material. One point of distinction to be particularly noted is that the layers 5, 6 and 7 are formed in two parts 5a, 5b, 6a, 6b, 7a and 7b, of which the upper part has the higher refractive index and lower band gap than the lower part. The refractive index of each of the intervening layers 2 and 3 is lower, and its band gap higher, than that of each of the two layers between which it is sandwiched, and those of layers 1 and 4 are lower respectively than those of their adjacent layers 5a and 7b. Another characteristic is that the refractive index and band gap of this upper part of each of the high refractive index layers are respectively higher and lower than the corresponding parameters of the upper part of the higher refractive index layer next beneath it.

These refractive index relationships mean that light guided by the ribs 10, 11 and 12 tends to concentrate in the upper parts 5a, 6a and 7a of layers 5, 6 and 7. These three layers are constructed of n-type material, while layers 2, 3 and 4 are made of p-type material. The p-type material at the end of each rib 11 and 12 is electrically isolated from the remainder by etched channels 21, 22 to produce small area low capacitance photodetectors 23, 24 in these regions. Alternatively the necessary isolation of the p-type material of the photodetectors can be achieved by proton bombardment, or the device could have been grown entirely in n-type material, the requisite p-n junctions being created subsequently for instance by diffusion.

If a frequency multiplexed signal is introduced into the rib waveguide 10 it will be coupled into tongue 13. The tongue will absorb light of all frequencies down to a limit, fo, determined by the band gap of the material of which it is made. At the root of the tongue, this material is covered with the higher refractive index lower band gap material of layer 6a, which will absorb light of frequencies down to a lower limit, fl, determined by its band gap. Part of any light within this band of frequencies, fo to fl, will be absorbed in the region of the photodetector 23 where it can provide a required signal output, while the rest is absorbed in the remainder of the layer and so prevented from creating a spurious signal in the next higher photodetector 24.

Light in the frequency band f1, to f2, where f2 is the lower frequency absorption limit

determined by the band gap of the material of layer 7a, is not absorbed by the material of layer 6a. Therefore light in this frequency band is guided by rib 11 before being coupled into tongue 14. In rib 11 the light tends to be concentrated in layer 6a by virtue of the fact that its refractive index is higher than that of the two layers between which it is sandwiched. If the material of layer 7b has a lower band gap than that of layer 6a it will absorb a band of frequencies at the upper end of the frequency band f1 to f2. However more normally the band gap will be made equal or higher than that of layer 6a so that the whole of this frequency band will be in principal available for detection by photodiode 24.

The minimum channel spacing that should be obtainable with this type of demultiplexer can be calculated from the amount of optical isolation required and the steepness of this absorption edge in the semiconductor materials used. An isolation of 15 dB will be taken as adequate for most PCM systems. The PCM passband characteristic of the demultiplexer tends to have poorer cut-off on the long wavelength side, where some of the unwanted signal is absorbed. Hence this is the region of the detection spectrum that limits channel capacity. The maximum allowable absorption for the unwanted signal can be expressed as a proportion of the absorption for the wanted signal. This is convenient for analysis because over a considerable portion of the band edge the absorption coefficient increases logarithmically with photon energy and therefore the ratio of the dB absorption for two signals of given photon energy separation remains constant (see Fig. 3) irrespective of the actual absorption and photon energy. In such circumstances the dB absorption of the wanted signal, over the length of the detector, should not be made larger than is necessary, otherwise a bigger proportion of the unwanted signal would be detected. A minimum figure of 3 dB absorption for the wanted signal is reasonable and gives up to 50% quantum efficiency of detection. For the unwanted signal to be 15 dB down on this value less than 1.6% should be absorbed, i.e. the attenuation of this signal must be less than 0.07 dB (through the detector). This requires an attenuation ratio between the two signals in dB of 43:1. To illustrate what this may mean in bandwidth, logarithmic plots of typical measured absorption edges of various compositions of (GaIn)(AsP) are given in Fig. 3. These are steeper at the lower end of the absorption range and in this region a 43:1 ratio in attenuation is obtained over a photon energy interval of about 0.027 eV. This shows that the demultiplexer can have a minimum reasonable channel spacing of about 0.04 eV—suitably larger than the fall off interval. The corresponding wavelength spacing is about 80nm around a centre wavelength of 1.55 μm and 55 nm around a centre wavelength of 1.3 μm. Such a spacing allows up to 2 or 3 channels in a typical fibre in both bands and gives a useful increase in total information capacity.

Fig. 2 illustrates how the basic structure of Fig. 1 can be adapted to form a channel dropping demultiplexer detector; Fig. 4 shows how it can be adapted to form a laser multiplexing device. The basic arrangement of layers is the same as for the demultiplexer of Fig. 2, and the refractive index and band gap stipulations that were set out in connection with that device apply also to this device, though the absolute values of these parameters will in general be different and also the relative thicknesses of the layers.

In this instance the etched channels 21 and 22 are replaced by channels 25 and 26 at the root of each rib 10 and 11, and serve to isolate the p-type material of the rib from the remainder.

In the region in front of each etched channel the rib constitutes a double heterostructure laser with distributed optical feedback being provided by a ribbed surface 40 contouring the exposed surfaces flanking the ribs. Thus in the case of rib 11 an active layer is formed by the portion of layer 6a in the rib sandwiched between lower refractive index regions 3 and 6b of opposite conductivity type. Light emitted from the active region of this laser will be launched in the forward direction into tongue 13, though a part of this emission that is emitted from the end face 41 of layer 6a will not be guided and hence will be lost. Light emitted in the reverse direction will be absorbed by the unpumped region 42 of layer 6a.

The laser light from rib 11 propagating in the tongue 13 is coupled through layer 2 into layers 5a and 5b which do not significantly attenuate this light because they both have higher band gaps than that of the laser active layer of rib 11. Thus this light is able to pass through the laser of rib 10 in such a way as to be multiplexed with the light output of that laser.

It will be appreciated that the top contacts of the photodetectors 23, 24 of the demultiplexer of Fig. 2, and to a lesser extent the top contacts of the lasers of the multiplexer of Fig. 4, are small and delicate giving rise to some difficulty in affixing leads to these contacts. These problems can be ameliorated by using a bridging contact arrangement to a larger area pad (no shown) provided on one side of the rib. One method of making such bridging contacts is described for instance in the paper by D. Boccon-Gibod and P. Harrop entitled 'High Performance and GaAs Schottky Barrier Divides using a Cantilevered Metal Contact' appearing in the Proceedings of the 8th European Microwave Conference (Paris 4–8 September 1978).

CLAIMS

1. An optical waveguiding device including a stack of two or more superimposed optical waveguiding structures separated by low index material that permits optical coupling to occur between adjacent pairs of the waveguiding structures where their relative profiles are such that light of the same frequency will propagate in the two members of the pair with matching phase velocities, wherein the members of the stack terminate in staggered relationship, and wherein the or each of the waveguiding structures other than that at the bottom of the stack terminates in an end region over at least a part of which the profile is modified to a shape which provides a modified phase velocity which matches that of light of the same frequency propagating in the underlying region of the next beneath waveguiding structure so as to effect optical coupling therebetween.

2. A device as claimed in claim 1 wherein optical waveguiding in each of said end regions is provided at least in part by a rib structure.

3. A device as claimed in claim 1 or 2 wherein said stack of two or more superimposed optical waveguiding structures is formed in semiconductive material.

4. A device as claimed in claim 3 wherein each of the waveguiding structures has an upper part having a higher refractive index and lower band gap than that of the lower part thereof wherein both parts have the same conductivity type, and wherein the material of the upper part has a higher refractive index and lower band gap than that of the upper part of the waveguiding structure next beneath it.

5. A device as claimed in claim 4 wherein said device is a channel dropping demultiplexer detector.

6. A device as claimed in claim 5 wherein the waveguiding structures are made in material of one conductivity type and are separated by low index material of the opposite conductivity type, wherein the higher index material of the upper part of each waveguiding structure is absent from the end of each waveguiding structure for a certain distance beyond which the upper part is covered with a portion of the low index material of the opposite conductivity type thereby forming a photodiode which portion is electrically isolated from the remainder of the low index material so that the photodiode p-n junction is electrically isolated from the p-n junction formed between the waveguiding structure and said remainder of the low index material.

7. A device as claimed in claim 4 wherein said device is a channel inserting multiplexer optical source.

8. A device as claimed in claim 7 wherein the waveguiding structures are made in material of one conductivity type and are separated by material of the opposite conductivity type, wherein the higher index material of the upper part of each waveguiding structure is absent from the end of each waveguiding structure for a certain distance beyond which the upper part is covered with a portion of the low index material of the opposite conductivity type thereby forming a light emissive diode which portion is electrically isolated from the remainder of the low index material.

9. A device as claimed in claim 8 wherein each said light emissive diode is provided with distributed optical feedback by means of a periodic contouring of the semiconductor surfaces of the two surfaces flanking the two sides of the diode so as to make the diode a laser.

10. An optical waveguiding device substantially as hereinbefore described with reference to the accompanying drawings.

11. A method of making an optical waveguiding device including a stack of two or more superimposed optical waveguiding structures separated by low index material that permits optical coupling to occur between adjacent pairs of the waveguiding structures where their relative profiles are such that light of the same frequency will propagate in the two members of the pair with matching phase velocities, wherein the stack of waveguiding structures and intervening low index material are formed from a succession of layers of semiconductive material epitaxially deposited upon a substrate, wherein portions of the layers are removed so that the members of the stack terminate in staggered relationship with each waveguiding structure other than that at the bottom of the stack terminates in a region of modified profile that provides a modified phase velocity which matches that of light of the same frequency propagating in the underlying region of the next-beneath waveguiding structure so as to effect optical coupling there between.

12. A method as claimed in claim 11 wherein the composition of the deposited layers is such that each of the waveguiding structures has an upper part having a higher refractive index than that of the lower part thereof, and wherein the material of the upper part has a lower band gap than that of the upper part of the waveguiding structure next beneath it.

13. A method as claimed in claim 12 wherein the composition of the deposited layers is such that the waveguiding structures are made in material of one conductivity type and are separated by low index material of the opposite conductivity type, wherein the higher index material of the upper part of each waveguiding structure is removed for a certain distance at the end thereof, and wherein the region of the p-n junction, formed between the upper part of the waveguiding structure

and the overlying low index material, immediately beyond the removed region is isolated from the remainder of that p-n junction so as to form an isolated photodiode structure.

14. A method as claimed in claim 12 wherein the composition of the deposited layers is such that the conductivity type of the low index material that separates the waveguiding structures to the opposite of that of the lower index material of the lower part of each of the waveguiding structures, wherein in a region near the end of each of the waveguiding structures a light emissive diode, whose output is coupled into the lower refractive index lower part of the waveguiding structure, is formed from the waveguiding structure and the low index material that covers it by a process including the step of removing a portion of the higher index upper part of the waveguiding structure and the overlying low index material to provide the diode with a p-n junction electrically isolated from the remainder of the junction formed between the said two layers.

15. A method as claimed in claim 14 wherein said process of forming each diode additionally includes the step of contouring providing distributed optical feedback by a contouring of the semi conductor surfaces flanking the two sides of the diode so as to form it into a laser.

16. A method of making an optical waveguiding device substantially a hereinbefore described with reference to the accompanying drawings.

17. An optical waveguiding device made by the method claimed in claims 11, 12, 13, 14, 15 or 16.

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